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THE RELEVANCE OF DETERMINING RESPONSIBILITY FOR VIOLATION OF POWER QUALITY IN TERMS OF VOLTAGE FLUCTUATIONS

***Purpose.** The purpose of work is the analysis of scientific and technical information for determination of expediency of researches on the determined calculations of individual share of suppliers and consumers in violation of quality of electric energy on indicators of fluctuations of voltage. **Methodology.** Today the indicators characterizing fluctuations of voltage aren't considered: scope of change of voltage (δU_t) and dose of a flicker (P_t). These indicators represent long changes of characteristics of tension that assumes potential opportunity for studying of regularities of their emergence and the determined distribution of responsibility for these violations between subjects. **Results.** As showed by results of research: fluctuations of voltage make negative impact on sight of the person and functioning of the electric equipment; in a network there is a large number of possible sources of fluctuation of tension; there are ways of identification of fluctuation of voltage; there are methods of decrease in fluctuation of voltage. The analysis of literature didn't reveal development by definition of responsibility of subjects for violation of requirements to quality of electric energy regarding fluctuations of voltage. **Originality.** Performance of development in this direction will make definition of responsibility for violation of quality of electric energy fuller and basic. **Practical value.** This research will allow to develop further the metering device which defines responsibility according to the current legislation, and has flexible algorithm for further improvement. to the legislation, also has flexible algorithm for further improvement.* References 12, figures 7.

Key words: **quality of the electric power, indicators of quality of the electric power, electromagnetic compatibility, fluctuations of tension, fliker, scope of change of tension, definition of responsibility.**

В статье рассмотрены физические процессы при колебаниях напряжения, способы измерения и расчетов показателей их характеризующих, влияние колебаний напряжения на электрооборудование и мероприятия по его снижению. Сделан вывод о целесообразности проведения исследований по определению ответственности субъектов в случае превышения колебаниями напряжения допустимых значений. Библ. 12, рис. 7.

Ключевые слова: **качество электроэнергии, показатели качества электроэнергии, электромагнитная совместимость, колебания напряжения, фликер, размах изменения напряжения, определение ответственности.**

Introduction. Electrical energy as a product is used in all spheres of human activity, has a set of specific properties, and is directly involved in creating other types of products, affecting their quality. The concept of electrical energy quality (EEQ) is different from the concept of quality of other types of products. Each electrical customer (EC) is designed to operate at actual nominal parameters of electric energy, which are characterized by indicators of electrical energy quality (IEEQ). Degree of conformity of real and nominal IEEQ established by GOST characterizes EEQ.

Maintenance of requirements for EEQ on-site production does not guarantee their availability at the place of consumption, as the IEEQ influence the technical characteristics of the network and EC modes and exploitation. EEQ is also characterized by the term «electromagnetic compatibility». Under electromagnetic compatibility they mean the ability of EC to function normally in its electromagnetic environment (in the electrical network to which it is connected), without creating unacceptable interference to other EC, operating in the same environment.

Problem definition. Increase EEQ is an actual task of development of power industry, aimed at reducing electricity losses, increasing the service life of electrical equipment, ensuring the conditions of the normal process of electrical consumers. An important condition for improving the EEQ in electric networks of Ukraine is the interested the subjects of distribution and consumption of electricity. The way to improve the interest to ensure the necessary EEQ passes through the introduction of financial responsibility of suppliers and consumers for exceeding pre-admissible deviation of the IEEQ, in particular, and voltage fluctuations (VF).

Today we can say that the development of methods and techniques for determining the equity entities of the distribution of electricity in the liability for breach of EEQ in three-phase power networks for the following IEEQ and their characteristics: coefficient of asymmetry of voltage on the negative sequence and zero sequence (K_{2U}, K_{0U}), distortion factor of sinusoidal voltage curve and the coefficient of the n-th harmonic component of the voltage (K_U, $K_{U(n)}$), as well as steady state voltage deviations (δU_y). A complex technique that combines three techniques mentioned is also developed [1-4].

Not considered indicators characterizing VF: magnitude of voltage change (δU_t) and flicker dose (P_t). These indicators, like previous ones, are long-lasting changes in stress characteristics, which suggests the potential for the study of the laws of their occurrence and the determined allocation of responsibility for such violations between subjects. Implementation of development in this area will make the determination of responsibility for violating EEQ more comprehensive and fundamental, that in the future will develop a metering device, which determines the liability according to the legislation in force, and has a flexible algorithm for further improvement. Such a device should fix the deviations of all the above parameters, and make a generalized conclusion about the responsibility of the parties.

The goal of the work is analysis of scientific and technical information to determine the feasibility studies on deterministic estimates the equity providers and consumers in violation of the EEQ in terms of voltage fluctuations.

Results of investigations. When electrical customers are working with rapidly changing shock loads, in the mains power consumption abrupt shocks arise. This causes a change in the mains voltage swings which can reach high values, for example, the inclusion of an asynchronous motor with a high starting current multiplicity. These phenomena are caused by technological installations with rapidly varying mode of operation, which is accompanied by lashing out active and reactive power, such as a drive reversing rolling mills, electric arc furnaces, welding machines, etc.

We represent the power supply of the consumer in the form of equivalent circuit (Fig. 1) in which $\underline{E}_{syst}$ is the equivalent EMF of the system; $\underline{U}$ is the voltage on the busbars of the receiving substation; $\underline{Z}_{syst}$ is the equivalent resistance of the connection with the system; $\underline{Z}_{load}$ is the equivalent resistance of the load of the enterprise.

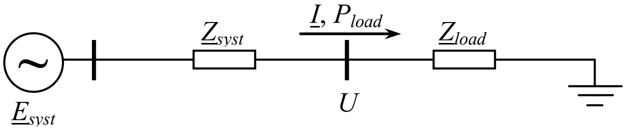

Fig. 1. Equivalent circuit of the customer's power supply

Changing of the voltage $\underline{U}$ on the busbars of the receiving substation caused by external to the electrical network of the consumer exposure, it can be seen as a consequence of changes in the EMF of the system $\underline{E}_{syst}$. On the assumption of the immutability of the load resistance ($\underline{Z}_{load}$ = const) the reduction of $\underline{E}_{syst}$ reduces the current I on the load lines and power consumer P_{load}, raising $\underline{E}_{syst}$ – to increase of I and P_{load}. In fact, when changing the voltage U the load resistance $\underline{Z}_{load}$ may vary somewhat, but in general, this change corresponds to a positive regulatory effect of active load voltage [5].

If the source of the VF is located in the electrical network of the consumer, the voltage $\underline{U}$ changes in the tire receiving substation is due to varying load at constant EMF system ($\underline{Z}_{load}$ = const). The value of voltage U is determined by the voltage drop on the resistance of the connection with the system $\underline{Z}_{syst}$. If we neglect the transverse component of the voltage drop, which is typical of the distribution network, we can write:

$$U = E_{syst} - \frac{P_{load} \cdot r_{syst} + Q_{load} \cdot x_{syst}}{U},$$

where P_{load}, Q_{load} are the powers of the customer's active and reactive load, respectively.

As mentioned above, VF is characterized by two parameters [5]:

- magnitude of the voltage fluctuation (δU_t), %;
- flicker dose (P_{st}, P_{Lt}).

The scope of the voltage δU_t is a quantity equal to the difference between the values and U_i and U_{i+1} consecutive extremes (or extremum and the horizontal portion) of the envelope of the fundamental frequency of the mean-square value of voltage values determined in each half period as a percentage of the nominal voltage.

The scale of change of voltage is calculated according to the formula, %:

$$\delta U_t = \frac{|U_i - U_{i+1}|}{U_{nom}} 100,$$

where U_i, U_{i+1} are the values of following one another extrema in accordance with Fig. 2.

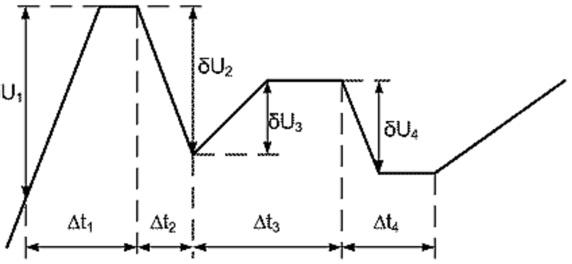

Fig. 2. Voltage fluctuations

Appearing at any point in the system VF distribute and toward the low voltage busbars substantially without attenuation, and the high-voltage bus bars - with damping amplitude. This effect is depending on the short circuit power ($S_{sc.syst}$) system. When propagating in any direction VF of the frequency spectrum is retained, and the attenuation factor or amplification ($K_{\delta Ut}$) [6] is given by:

$$K_{\delta U_t} = 1 + (S_{sc.syst} / S_{nom.t}) \cdot U_{sc},$$

where $S_{sc.syst}$ is the power of the short circuit of the system; $S_{nom.t}$ is the rated power of the transformer; U_{sc} is the voltage of the transformer short circuit.

Repetition frequency of voltage changes ($f_{\delta Ut}$), (1/s, 1/min) is determined by the expression:

$$f_{\delta U_t} = m / T,$$

where m is number of voltage changes by the time T; T is the time measuring interval taken equal to 10 minutes.

If two voltage changes are occurring at intervals less than 30 ms, then they are treated as one. The time interval between the voltage changes is:

$$\Delta t_{i,i+1} = t_{i,i+1} - t_i .$$

Assessment of the admissibility of the range of voltage changes by means of the curve of the permissible range of fluctuations of the frequency of repetitions of voltage changes or the time interval between successive voltage changes (Fig. 3).

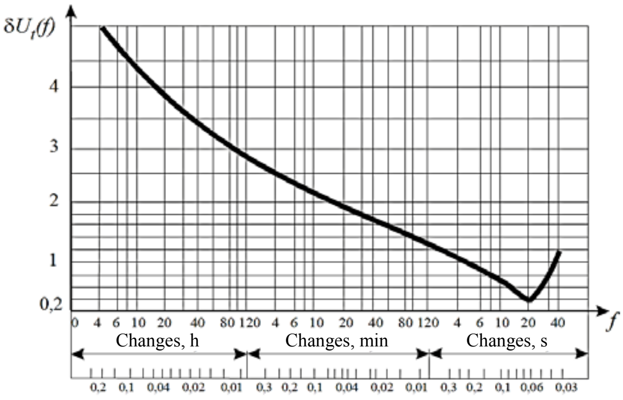

Fig. 3. Curves of permitted values $\delta U_t(f)$

EEQ at the point of common coupling with periodic VF, meander-shaped (rectangular, Fig. 4), according to the relevant requirements of the standard, if the measured amplitude of voltage changes do not exceed the values defined by the curve of Fig. 3, for relevant repetition of frequency of voltage variations ($F_{\delta Ut}$) or the interval between the voltage change ($\Delta t_{i,i+1}$).

The duration of the voltage measurement is the time interval from the start of a single measurement to its final value [5].

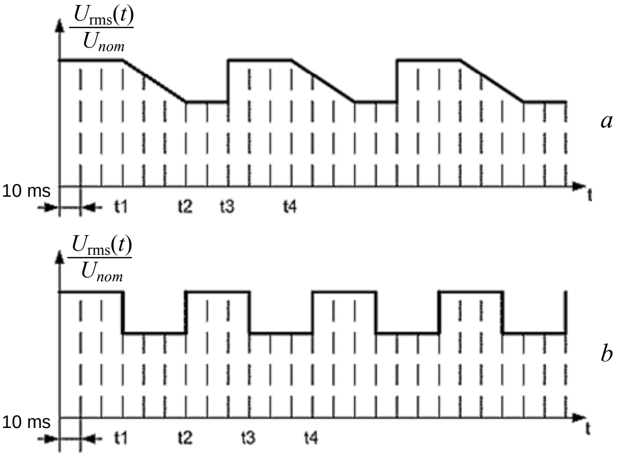

Fig. 4. Voltage fluctuations of arbitrary shape (*a*)
and meander-shaped (*b*)

On the other hand based on [7] there is used the method of «partial reactions» [8], the objective and unambiguous assessment of the VF is only possible by a dose of flicker.

VF of power supply (typically of less than 1 min), including the single quick change of voltage, cause the occurrence of flicker.

Flicker is subjective human perception of the luminous flux of artificial light sources fluctuations caused by fluctuations in the mains voltage, which supplies of these sources [5].

The intensity of the voltage flicker characteristic power VF taking into account the characteristics of visual perception and brain human vibrations of the luminous flux of incandescent lamps completely like VF. Incandescent lamps are the most massive loads sensitive to the VF to a greater extent than television sets, computers, electronic and microelectronic control. Intensity Flicker is expressed in dimensionless units; ordinates of the standard curve of acceptable values VF $\delta U_t(f)$ (Fig. 3) corresponds-corresponding values flicker intensity determined over 10 minutes with a probability of 99 % $P_{St} = 1$.

Flicker dose is a measure of human susceptibility to the effects of fluctuations in the luminous flux caused by VF in the supply network for a specified period of time, which is measured by the standard flickermeter.

Time perception of flicker is the minimum time to subjective human perception of flicker, voltage fluctuations caused by certain shape.

Standard [5] determines a short-term P_{St} and long-term P_{Lt} flicker dose (determined in short term observation time interval equal to 10 minutes at a long interval – 2 hours). Initial data for calculation are the flicker levels, measured by flickermeter – a device, which is modeled sensitivity curve (frequency response) of the human organ of vision [9].

The visual perception process when VF is simulated on the basis of the theory of the passage of the composite signal through a nonlinear dynamical system. Fig. 5 shows the frequency response of the visual analyzer, adopted by the IEC. The upper limit of the frequency of the VF, affecting vision, taking into account the time constant of the filaments of incandescent lamps is about 35 Hz at $\delta U_t\ t \le 10$ % [10].

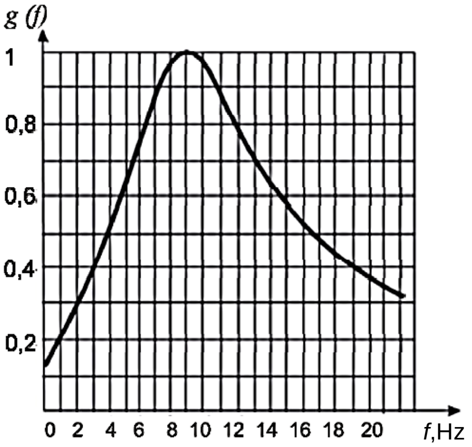

Fig. 5. Frequency response of the visual analyzer

where $g(f)$ is the variable coefficient of amplification of the inertial system (eyes), dependent on the oscillation frequency f.

The short-term flicker dose (P_{St}) can be determined by calculation making measurements on the observation interval TS = 10 min. In this case, the following formula:

$$P_{st}=\sqrt{\begin{array}{l}0{,}0314\,P_{0,1}+0{,}0525\,P_{1s}+0{,}0657\,P_{3s}+\\+\,0{,}28\,P_{10s}+0{,}08\,P_{50s}\end{array}},$$

where $P_{0,1}$, P_{1S}, P_{3S}, P_{10S}, P_{50S} are the levels of flicker, which values have been exceeded during 0.1; 1; 3;10; and 50 % of the time interval of observation T_s. Index «*s*» in the formula indicates smoothed values P_1, P_3, P_{10}, P_{50}. Smoothed values are calculated by the following formulae [5]:

$$P_{50s}=(P_{30}+P_{50}+P_{80})/3\,;$$

$$P_{10s}=(P_6+P_8+P_{10}+P_{13}+P_{17})/5\,;$$

$$P_{3s}=(P_{2,2}+P_3+P_4)/3\,;$$

$$P_{1s}=(P_{0,7}+P_1+P_{1,5})/3\,.$$

Because the time constant of the device is 0.3 s, the $P_{0,1}$ value can not be changed quickly and for $P_{0,1}$ smoothing is not required.

Interval of 10 min of observation, used in assessing the short-term flicker, convenient to assess VF created by technical means with a short duty cycle. In cases where it is necessary to take into account the cumulative effect of several loads of interfering randomly (e.g., welding machines, electrical motors), or take into account the sources of flicker with a long and varying the duty cycle (e.g., electric arc furnace), it is necessary to assess the long-term flicker dose. For this long-term dose of flicker (P_{Lt}) is determined based on the measurement of short-term doses of flicker (P_{Lt}) with respect to the period of observation, associated with long working duty cycle or period during which the observer can perceive flicker, such as a few hours, using the expression:

$$P_{Lt}=\sqrt[3]{\frac{1}{12}\sum_{k=1}^{12}(P_{stk})^3}$$

where P_{Stk} (i = 1, 2, ... N) are the successive values of short-term flicker dose on k-th time interval T_S for a long-term observation period T_L [5].

EEQ by the flicker dose meets the requirements of the Standard, if the short-term and long-term flicker determined by measuring for 24 hours, or calculation, do not exceed the limit values: for short-term flicker – 1.38 and for long-term – 1.0 (at VF with a shape different from the meander) [11].

Voltage fluctuations in the power network lead to the following consequences:

- fluctuations in the luminous flux of lighting (flicker effect);
- deterioration of the quality of television receivers;
- violation of the x-ray equipment;
- false operation of control devices and computers;
- malfunction of converters;
- torque fluctuations on the shaft of rotating machines, causing additional power losses and increased wear and tear, as well as violations of technological processes that require a stable speed.

The degree of influence on the operation of the equipment is determined by the oscillation amplitude and frequency.

Load fluctuations of high power, for example, rolling mills, causing a moment's hesitation, active and reactive power local power generators.

Vibrations and voltage dips deeper than 10 % may result in the extinction of the discharge lamp re-ignition, depending on which type of lamp can occur only after a considerable period of time. With deep vibrations and voltage failures (more than 15 %) may fall contacts of magnetic starter, causing disruptions in production.

Sharp VF have negative impact on the dynamics of movement of trains. Current jumps and traction caused VF, reduce the reliability of the contactors and are dangerous in terms of occurrence of slipping. For electric rolling fluctuations are dangerous of the order of 4-5%.

The increase in electricity losses during in-plant networks caused by VF with amplitude of 3 %, does not exceed than 2 % of the initial value of the losses.

A the metallurgical factories VF more than 3% lead to a mismatch of speeds drives continuous stands of metal rolling, which reduces the quality (stability of thickness) of the rolled strip.

In the production of chlorine and caustic soda VF cause a sharp increase in anode wear and decrease performance.

Voltage drops when producing chemical fiber stop cause the equipment to which the restart of 15 minutes spent in the event of failure of the equipment 10 % to 24 h at 100 % of equipment failure. Reject product is from 2.2 to 800 % of the tonnage of the technological cycle. Time of the full restoration of technological process is up to 3 days.

Noticeable influence fluctuations and voltage drops at low power asynchronous motors. This poses a risk for textile, paper-making and other industries with high demands on the stability of the rotation speed of electric drives. In particular, the VF on chemical fiber plants lead to a non-stable rotation of the winding device. As a result, nylon thread, torn, or manufactured with non-uniform thickness.

GOST 32144-2013 determines the effect of VF on lighting systems that affect a person's vision. Blinking light lamps (flicker effect) causes bad psychological effect of fatigue and body as a whole. The degree of eye irritation depends on the size and frequency of blinking. The strongest impact on the human eye blinking light having a frequency of 3 ... 10 Hz, so the allowable fluctuation range of the voltage in the low: less than 0.5 %. The degree of influence depends on the type of light source. For example, under the same VF incandescent lamps have a much greater impact than discharge lamps [5].

VF with amplitudes of 10 ... 15 % can lead to failure of the capacitor, and the gate rectifier units.

In the steel mills to the number of receivers that are sensitive to the VF are continuous mills rolling.

When VF arise swing turbogenerators. For turbogenerators themselves are not dangerous swing, however, being transferred to the turbine blades, they can activate the speed controllers.

Noticeable is influence on VF asynchronous motors of small capacity. Fluctuations are unacceptable for the textile, paper-making and other industries, particularly high demands on the accuracy of maintenance of speed drives, which are mainly used asynchronous motors.

We studied in detail the effect of voltage fluctuations in the electrolysis plants. VF with amplitudes of 5 % caused a sharp increase in anode wear and reduced service life.

VFs have a significant impact on the resistance welding. This affects both the impact on the quality of the welding process, and welding control operation unreliability. On the voltage quality in resistance welding networks imposed severe restrictions on the scope of voltage changes: 5 % to weld ordinary steel, and 3 % for the welding of titanium and other high-temperature steels and alloys. Duration of admissible VF management apparatus resistance welding machines is limited to no more than 0.2 s to avoid false operation of these devices.

VF adversely affect the operation of radio equipment, disrupting their normal operation and reduces service life. Interference in television pictures appear at frequencies of 0.5 … 3 Hz and noticeable mainly in still images.

For power consumers sensitive to VF, are also computers, X-ray machines, etc. When operating in the computer control mode is sometimes only one or two scale fluctuations with 1 ... 1.5 %, so that a failure has occurred in any cell of the machine and, as a consequence, any error in control commands or in the calculations carrying out.

Measures to reduce VF. Separation of loads and static reactive power compensators (STC) are used to reduce VF.

Separation of loads. To separate rapidly changing and relaxed loads various circuits and devices can be used. The simplest is a scheme based on the use of a dual reactor: calm and rapidly changing load connected to different sections (windings) of the reactor (Fig. 6). Due to the fact that the mutual ratio between sections $M \neq 0$, the voltage drop in each of them at load currents I_1 and I_2 are represented by expressions:

$$\Delta U_1 = jx_L \cdot (I_1 - k_M \cdot I_2);$$

$$\Delta U_2 = jx_L \cdot (I_2 - k_M \cdot I_1),$$

where x_L is the inductive reactance of the reactor section; $k_M = M/L$ is the mutual inductance factor $k_M = 0.5$-0.6.

In the ideal case when $I_1 = I_2$ we have:

$$\Delta U = I_{1(2)} \cdot x_L (1 - k_M).$$

The voltage drop due to mutual inductive connection is reduced by 50-60 %. When $I_1 \neq I_2$ decrease in the value of ΔU is obviously smaller. Scale voltage changes depending on the resistance of the melting energy system to the busbars, which is connected to the reactor.

Application of this scheme to connect the electrical arc furnace (ДСП – 5МТ) and can, in some cases, to provide on the busbars «relaxed» load VF whose value does not exceed maximum permissible value.

Application of dual reactor more efficient when the coupling coefficient between the windings (sections) is equal to unity; this is possible by using reactors with iron core. In this case, you can select the parameters of the reactor so that the influence voltage drop caused by a load resistance section to an adjacent mains.

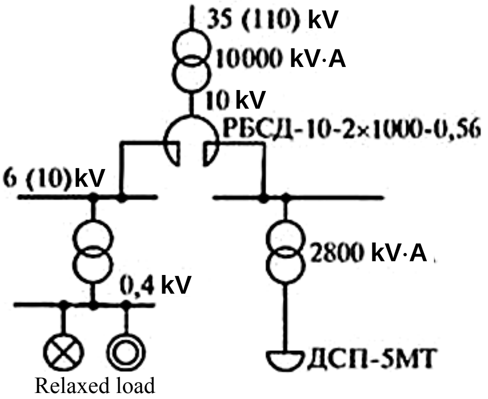

Fig. 6. A circuit using a double reactor for voltage stabilization at shock loads

For rapidly changing and relaxed loads transformer with split windings are also used. When connected to one branch of the LV transformer winding calm load, and the other – rapidly changing relationship between the values of the Range of voltage change at the respective busbars ΔU_1 and ΔU_2 and can be represented as:

$$\Delta U_1 = \Delta U_2 \cdot \frac{4 - k_s}{4 + k_s},$$

where $k_s$is the splitting factor of 3.34 – 3.64. The average value is taken $k_s = 3.5$.

When we extract rapidly changing load on a separate transformer overall resistance is reduced to the value of:

$$X = \frac{X_{T1} \cdot X_{T2}}{X_{T1} + X_{T2}} + X_C,$$

till the value X_C. Then the scope of the VF on a stable load busbars decreases X_C/X times, and on busbars of rapidly changing load it increases $X/(X_C+X_{T2})$ times [11].

When using transformers with split windings for networks 6-10 kV electric arc steelmaking furnace of small capacity VF on busbars of «relaxed» load can also be within acceptable limits.

Reducing the VF by using STC. VF compensation in this case is carried out by compensating reactive power (RP) surges. For compensating the effect of the time lag in the generation of the RP compensator should be minimal, so as not to cause an increase in the level of the VF. For example, if compensation pounce RP rectangular shape (Fig. 7,*a*) with a certain time lag Δt instead of one there are two pounce RP (Fig. 7,*b*), and the level of the VF increases.

Equally important is the question of choosing the power of the STC. Maximum capacity compensating STC related to the maximum span VF, which can be compensated for, by the following expression:

$$Q_{k.\max} = Q_{\max} \cdot \left(1 - \frac{1}{P_{st}}\right),$$

where P_{st} is the flicker intensity.

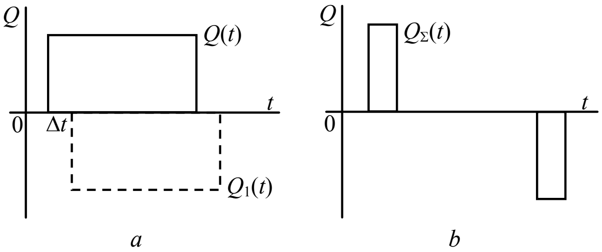

Fig. 7. Graphs of changing of load's RP: *a*) summary graph of load's RP and STC's RP (solid line) and STC's load (dotted line); *b*) summary graph of load's RP and STC's RP

The calculation of this formula gives overestimated results (the error of 5-10 % depending on the degree-fine dispersion range of the VF) [12].

In addition to the activities listed above must use the best solutions, we scheme with minimal additional power-governmental expenses, which include:

- approaching the high voltage source to large power consumers with rapidly changing load;
- reduce the induced drag of the external power supply lines (e.g., rejection of busbars, a decrease in the inductance of the reactors);
- provide power to large power consumers with rapidly changing load on individual lines coming directly from the power supply (main substations, heat-electric generating plants, and others);
- compliance with the optimal level of short-circuit power in the network feeding the power-consuming equipment with rapidly changing load within 750-10000 MVA;
- to limit the self-starting motor at VF planned to reduce, if possible, the time of action and automatic circuit reclosers and application of high-speed network security, as well as the use partial step in which the most important are only the engines, and the rest are disabled;
- use the parallel operation of power lines and transformers in the main substations (with the closed section switch);
- to limit the VF at consumers voltage loss in the line reactor in normal operation should be no more than 4-5 % of the rated voltage;
- reduction of the supply network impedances. By increasing the sectional line conductors is reduced (*R*), and the application of series compensation device reduces the total (*X*). Disadvantages are increased capital costs, and the use of a longitudinal compensation is dangerous rise in short-circuit current at ($X \to 0$).

Conclusions.

1. The problem of voltage fluctuation is relevant because:

- voltage fluctuations have a negative impact on human vision and operation of electrical equipment;
- the network has a large number of possible sources of voltage fluctuations;
- there are ways to identify and methods to reduce voltage fluctuations.

2. It is required to ensure the interest of the subjects of the distribution process and to reduce the energy consumption level of the VF to acceptable values. As an incentive to promote the interest of the authors consider the introduction of subjects of responsibility for violation of requirements for the EEQ, in particular VF.

3. Analysis of the literature revealed no developments to identify the subjects of responsibility for violation of requirements for the EEQ in terms of voltage fluctuations.

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